Building a Pathway to Mars:
Mars Technology Program Analysis and Case Study

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Abstract— The exploration of Mars has been the focus of increasing scientific interest aimed at addressing a number of enduring questions about the planet and its relationship to Earth. These include determination of existing life on the planet, evidence of any earlier living organisms (e.g., fossils), and global climate processes. NASA's Mars Exploration Program is formulated to link scientific goals and objectives to those sets of missions that will best enable the fulfillment of scientific goals while retaining resiliency to unexpected events such as unforeseen discoveries, random failures, or budgetary uncertainties.

This paper focuses on the analysis and identification of technology development portfolios designed to meet the scientific and mission objectives of the Mars Exploration Program. A multi-criteria decision-making approach was developed to address the question, "Given a Mars exploration program and budget composed of candidate mission concepts dependent on a variety of alternative technology development programs, which combination of technologies would enable missions to maximize science return meeting the largest number of scientific objectives under a constrained budget level?" A number of R&D portfolio planning techniques were employed to address this question.

Technology contribution to missions was measured using decision analysis techniques. Uncertainties in the capability requirements of each technology were captured using performance attributes and their probability distributions to represent development outcomes. The ability of each technology to meet technology capability performance requirements was measured through probabilities of success estimated by technology developers and program managers. Monte Carlo simulation of technology development outcomes was simulated for each mission portfolio examined. The scientific value of each portfolio was computed based on each portfolio's contribution to a strategic exploration goal. Finally, the total cost of each portfolio was computed and tested against a technology budget constraint. Different budget profiles over a twelve-year planning horizon were examined and sorted by cost to remove portfolios exceeding the budget constraint. Solutions were found by searching all possible portfolios for the maximum science value at the lowest cost.

These calculations were performed for every possible combination of portfolios (2047 cases). Example solutions, implications, and observations are discussed.

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1. INTRODUCTION

There has been considerable interest in the scientific community and at NASA in addressing fundamental questions about the planet Mars [1, 2, 3]. NASA's program for the exploration of Mars is linked to a need for numerous enabling technologies that must be developed in order to proceed with the variety of missions planned.

A diverse mixture of programmatic issues face the Mars Exploration Program. The complex interactions between scientific interests, missions, technologies, and budgets amplified the need for an organizing structure to provide insights about high-value technologies and mission sensitivities to technology development uncertainties and budget constraints. The purpose of this paper is to describe such an organizing structure used to address this problem.

A combined approach was developed for analyzing portfolios of technology investments using multi-criteria decision analysis, Monte Carlo simulation, and mathematical programming techniques [4, 5, 6]. The approach enumerated every possible technology portfolio combination in order to identify sets of highest science-value missions and technologies that could be funded within a specified budget. This was done in a stepwise

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fashion by simulating the uncertainties in every technology required by every mission. If, during the simulation, a technology development failed, its parent mission was removed from the portfolio. The science value of the remaining missions was then computed and the total technology cost by year was compared to the budget for feasibility.

This process was repeated to obtain the probabilistic uncertainties and their impacts on technology outcomes. The resulting outcomes were sorted by science value, technology value, cost feasibility, and, in some cases, minimum cost and maximum number of enabled missions.

The approach and results obtained were viewed to have value in unraveling the interdependencies of the Mars Exploration Program. Many of the varied planning concerns (mission candidates, science value, technology risk, uncertainty, investment costs, budget, and time) could be aggregated in a fashion that allowed planners to quantify the overall effect of alternative assumptions and possible actions on the Program.

This paper represents a first attempt to apply multi-criteria decision techniques to the Mars technology R&D program. A brief description of the Mars missions, technologies and cost assumptions is presented first. The next section describes the approach followed by the results obtained. The last section provides a discussion of these results and the conclusions.

2. FINDING THE PATHWAY

Finding a path to Mars in the context of conflicting science objectives, mission requirements, uncertain technologies, and limited resources is fraught with innumerable possibilities. As a first step, this section defines the scope of the problem in terms of the science objectives, the missions considered, the technologies evaluated, and the assumptions made.

The science objectives for the Mars Exploration Program were, at the time of this study, divided into three categories aimed at addressing three over-arching questions:

1. Is there life on Mars?
2. If not, has there ever been life on Mars?
3. What happened to the climate on Mars?

These questions had been translated into a number of strategic "pathways" designed to address each question through scientific measurements [3]. The emphasis of the pathways was a weighted sum of eight levels of priorities assigned to one hundred ninety-two scientific measurements. The three pathways included: a Mars in-situ strategy, a Mars sample return strategy, and a global cycles and climate strategy. This paper reports on the results of a combined strategy that was a weighted

combination of the three science pathways with an emphasis on in-situ exploration. The pathway emphasis implied a different set of scientific measurements. The three pathways were based on one hundred and ninety-two scientific measurements classified into eight priority levels. In this study an emphasis on in-situ science utilized a <60%, 20%, 20%> allocation of science measurements to the in-situ, Mars sample return, and global climate pathways. Thus, sixty percent of the total number of measurements was allotted to in-situ missions, and twenty percent each to the other pathway missions.

The missions considered for implementing each scientific pathway are summarized in Table 1. The alternatives included 3 lander/rover missions, 2 lander/drilling system missions, 4 orbiter missions, a Mars sample return mission, and 1 low-cost opportunity mission called "Scout" as a placeholder for what was anticipated to evolve into a series of low-cost mission concepts.

Table 1. Mars Mission Candidates

Mission Name	Description
Polar Layer Deposit Rover	Rover mission to characterize polar regions with in-situ sampling
Volcanology Rover	Rover mission to characterize volcanic region with in-situ sampling
Rover/Lander	Rover to characterize landing site with in-situ sampling
Wildcat Lander	Lander with 30m depth drilling system
Sabertooth Lander	Lander with 1000m depth drilling system
Synthetic Aperture Radar Orbiter	Orbiter sounding for surface science experiments and mapping
Magnetometer Orbiter	Orbiter for magnetometer and gravity instrument science
Imaging/Atmospheric Sounding Orbiter	Next generation remote sensing orbiter (Imaging and atmospheric sounding)
Surface Science Orbiter	Orbiter for large-scale (area) surface science
MSR Sample Lander	Sample return with a Mars ascent vehicle
Scout Mission	Low-cost opportunity mission

It should be noted the missions in Table 1 were candidate missions that, in some cases, served as placeholders for evolving mission concepts and science pathways. In some cases, only one of 2 orbiter concepts might be chosen or 2 of 3 landers were planned. The determining factor in such cases was often the technology development cost or cost coupled with the technology development requirements and development challenges (chance of success).

Each of these missions had a variety of requirements for enabling technologies. A list of 110 technologies was divided into 14 representative categories. A performance attribute was defined to characterize each technology category requirement and corresponding technology development task. Table 2 lists the high-level attributes and their definitions.

The technology capabilities in Table 2 were then mapped to the missions in Table 1 to define a roadmap of enabling technologies by mission. The eleven missions mapped to a total of 18 unique technology requirements. This was due to sharing of common requirements by some missions and a natural partitioning between rover, lander, and orbiter missions. In each of these eighteen cases, a data set was obtained from technologists, mission designers, or available documentation. Table 3 lists the data items gathered for each technology attribute.

Finding a feasible pathway through the large number of possible technology investments would require combining Tables 1, 2, and 3 in a manner that would amplify the high-science-value, high-technology-capability, low-risk, and low-cost technologies while discounting the less promising (i.e., lower performing and risky) and more expensive technologies.

A systematic approach was developed to address the question of identifying high-value technology investment portfolios by enumerating every possible technology portfolio combination and searching for the lowest technology cost portfolio that enabled the most science. The resulting technology portfolio(s) would thus provide guidance on where technology investments should be made for the science pathway strategy. The next section describes the approach used to find this pathway.

3. APPROACH

The process used is illustrated in Figure 1. The first two steps (1, 2) culminated in Table 1, the next two steps (3, 4) produced Table 2, and step 5 was captured by Table 3. The remaining step (6), for evaluating the alternative portfolios, is the focus of this section.

The problem described above can be restated in the following mathematical terms. Let the technology attributes be defined as random variables $x_1, x_2, ..., x_n$ each with probability density functions $f_1(x_1), f_2(x_2), ..., f_n(x_n)$.

Table 2. Technology Performance Attributes

Technology	Attribute Definition
Precision Landing	Semi-major axis ellipse distance, kilometers. Width of landing ellipse with 99% landing probability
Impact Attenuation	Landing survivability, meters. Free-fall distance at terminal landing phase for pallet-based landers
Hazard Avoidance	Average size of identifiable rock on 30 degree slope to be avoided during landing.
On-orbit Science	Resolution of primary instrument, meters/pixel.
Forward Planetary Protection	Number of organisms present on the spacecraft (thousands)
Surface Sample Characterization	Technology Readiness Level of instrument package designed for Mars surface sampling. Measured on 1-9 scale using a narrative definition [7].
Sub-surface access (drilling) technologies	Achievable depth of drilling subsystem, meters. Two cases: shallow (30m) and deep (1000m) technologies
Surface Mobility	Distance capable of roving, meters per Sol (Martian day)
Surface Sample Handling	Sample cross-contamination limit, parts per million.
Back Planetary Protection	Minimum containment size of particle within sample return system, microns.
Mars Proximity Data Rate	Data rate among communications systems (and missions) at Mars, megabits/second.
Mars Orbit Rendezvous	Sample capture system energy requirements, meters/second
Multi-mission Survivability	Infrastructure technologies to extend component lifetimes, Sols. Two cases: on-orbit and surface technologies.
Scout-non-specific Technology	Placeholder for cost allocation to Scout investment (0-1 level with probability of success 0.95).

Table 3. Data Inputs for Mars Technologies

Data Item	Description
Technology Capability Estimate	Estimate of technology attribute requirement outcome given technology development budget and development task is 100% successful. Value can be a point estimate, range, or probability distribution.
Probability of Success	Estimate of probability of technology development task success (based on likelihood of budget changes, dependencies on external developments, task complexity.
Default outcome	Likely value of technology attribute outcome if technology development fails completely or partially. Use state-of-the-art or descope option.
Technology Budget Constraint Profile	Resources planned for development task in 3-year increments over a twelve-year planning horizon, real-year dollars.

Let the technology capability value for each attribute be represented by an attribute value function that maps the range of each attribute to a value between zero and one. Using a multi-attribute decision analysis approach [5], the best state of each attribute was scaled to a value of one and the worst state of the attribute was defined as having zero value.
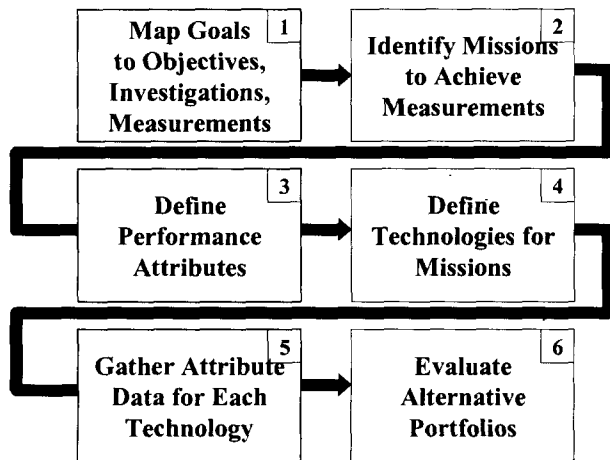

Figure 1. Mars Portfolio Analysis Approach

It can be shown that attribute value functions $v_1(x_1)$, $v_2(x_2), \ldots, v_n(x_n)$ that can be used (under an assumption of preferential independence) to compute a multiattribute value function for the portfolio of each technology set within a mission:

$$V(\text{Mission } i) = V(\underline{x}_1, \underline{x}_2, \ldots, \underline{x}_n) = \sum_{j=1}^{n} k_j v_j(\underline{x}_j)$$

where the $\underline{x}_j$, represent the mission-specific realizations of technology j. To compute a measure of technology value for a mission, i, the values of each attribute were substituted in the corresponding value functions and V(i) was computed for each mission. However, the attributes were random variables with empirical probability distributions whose uncertainties had to be transformed through attribute value functions into a probability

distribution for V(i). This was done using Monte Carlo simulation to generate technology expected values that reflected the uncertainties of each technology task. During this process, technology tasks failed in accordance with their estimated task probabilities of success (Table 3) and in those cases, the predefined default value was used in place of the sampled value. Because the technologies were considered enabling for the missions depending on them, a technology failure within a mission was equivalent to removing the mission from the portfolio for a single Monte Carlo trial. The technology values for each of the remaining missions in the portfolio (i.e., technologies that succeeded) were computed in the same manner. It should be noted that temporal dependencies between missions were not considered.

To obtain a first-order metric representing the aggregate technology portfolio capability, the maximum of the technology values for the portfolio was adopted. The aim of using the maximum criterion was to push portfolios containing a high technology capability toward the top of the rankings. In a similar manner, the maximum criterion was also used to assign the science value of the portfolio. Each mission technology value was multiplied by a science value weight representing the proportion of priority science measurements addressed by that mission. Thus, if a portfolio had a low technology value and high or low science value, the result would be low. If the portfolio had a high technology value and high or low science value, the result would be high or low science value, respectively.

After the simulation was completed, the technology costs for each year in the planning horizon were subtracted from an externally specified budget constraint value to determine whether the portfolio as specified was economically feasible. Three budget profiles were examined: 25, 50, and 75 million dollars per year (real-year dollars). A first-order feasibility criterion was used to determine cost feasibility--if the total technology costs exceeded the budget for any year, the portfolio was declared infeasible and discarded. It should be noted that

no attempt was made to shift budget funds and technology costs to resolve feasibility problems. The portfolio results were then output to a file, a new portfolio combination was defined, and the entire process repeated until every possible combination of missions had been considered. This required a separate Monte Carlo simulation for each of 2047 portfolios (2^n-1 combinations). A search was conducted by sorting the output file to find the portfolio with highest expected science value based on the enabling technologies that could be developed within a given budget.

4. RESULTS

Although a number of cases and sensitivity studies were examined, this paper reports on the primary results obtained for technology budget profiles of \$25M/yr, \$50M/yr, and \$75M/yr per year. The results provided insights into which technologies were important for strategic funding and also identified missions enabled by those technologies. Table 4 summarizes the baseline results for each of the three budget assumptions.

At the \$25M/yr technology budget, only 15 out of the 2047 portfolios met the budget constraint. The orbiters had the lowest technology costs that fit within the budget profile. The striking result was that although this was the in-situ science pathway, none of the in-situ options were affordable—at the lowest budget assumption the in-situ exploration option was not feasible.

At the \$50M/yr technology budget, the number of affordable technology portfolios increased to 225 out of 2047 possibilities that allowed eleven additional technologies to enter the solution. The results for minimum cost and maximization of enabled missions are also provided to illustrate additional criteria and the range of options. The minimum cost option enabled the fewest missions (3) while the maximum enabled mission option cost substantially more. From these results it was clear that the \$50M/yr budget had opened the trade-off space between technologies and enabled missions.

All 2047 portfolios fit within the budget constraint at the \$75M/yr level that included all 14 technologies. As a result, all the missions in Table 1 were enabled at this funding level. The fact that an additional \$25M/yr allowed only three remaining technologies beyond the \$50M/yr case was an indication that many of the technology trade-offs were likely to be in the neighborhood of \$50M/yr, (for example, from \$40-60M/yr).

5. DISCUSSION AND CONCLUSIONS

The results were presented to the Mars Systems Engineering Team and endorsed by that group as providing valuable insights and benefits for Mars Program planning. During the course of their review, a number of key areas were identified for further improvements.

Benefits

The first benefit of the methodology was in providing a systematic approach that addressed four critical issues to the Mars Exploration Program: (1) identifying key technologies and their risks to candidate mission concepts; (2) linking science objectives to technology selection; (3) inclusion of technological uncertainties; (4) application of costs and budget constraints to the selection of feasible technologies. In particular, the ability to provide an audit trail through the process from science objectives to technology capabilities to enabled missions and ultimately the feasible technology portfolios was viewed as a major contribution.

A second benefit was in capturing key aspects of the problem facing Mars Program planners. The relationships between technologies, risks, costs, missions, and budget constraints embodied a complex nest of interactions making it difficult to unravel the effects of adding or deleting technologies, modifying science objectives, or changing budgets and costs. The approach aided in managing these effects by modeling important relationships in a consistent manner that allowed a variety of planning assumptions to be tested.

A third benefit was the ability of the methodology, and particularly the software tool, to enumerate and evaluate every possible mission technology portfolio. This provided an additional level of confidence in the approach that every case possible had been considered rather than some limited set produced by a working group or because of limited modeling capabilities.

A fourth unexpected benefit was the enhancement of communication between Mars Program mission planners and technologists. It was observed that mission planners sometimes levied requirements they viewed as goals whereas the technologists viewed the requirements as fixed and had assumptions and constraints about the requirements not communicated clearly to the mission planners. The interactive process of gathering the data for Table 3 raised awareness and clarified understanding about assumptions, budgets, and work efforts not clearly understood or defined prior to the exercise.

Table 4. Mars Technology Portfolio Results for Three Investment Levels
Showing Feasible Technologies and Missions Enabled

Technology Investment	Technology Portfolio (at minimum total technology cost)	Minimum and Maximum Number of Missions Enabled
$25M Per Year	❑ On-orbit science ❑ Telcom network & navigation ❑ Multi-mission survivability, orbiters	❑ Magnetometer orbiter ❑ Synthetic Aperture Radar orbiter ❑ Imaging/Atmospheric Sounding orbiter ❑ Surface Science orbiter
$50M Per Year	❑ Precision landing ❑ Impact attenuation ❑ Hazard avoidance ❑ On-orbit science ❑ Forward planetary protection ❑ Sample characterization, surface ❑ Sub-surface access ❑ Mobility ❑ Sample handling, contamination ❑ Back planetary protection ❑ Telecom network, navigation ❑ Mars Orbit Rendezvous ❑ Multimission survivability ❑ Scout technology	Minimum number of missions: ❑ Mars Smart Lander ❑ Mars Sample Return ❑ Scout mission Maximum number of missions[a]: ❑ Volcanology Rover ❑ Mars Smart Lander ❑ Magnetometer orbiter ❑ Polar Layer Deposit Lander/Rover ❑ Wildcat Lander ❑ Sabertooth Lander ❑ Scout mission [a]Excludes On-orbit science, back planetary protection, Mars orbit rendezvous, and multimission survivability
$75M Per Year	❑ Precision landing ❑ Impact attenuation ❑ Hazard avoidance ❑ On-orbit science ❑ Forward planetary protection ❑ Sample characterization, surface ❑ Sub-surface access ❑ Mobility ❑ Sample handling, contamination ❑ Back planetary protection ❑ Telecom network, navigation ❑ Mars Orbit Rendezvous ❑ Multimission survivability ❑ Scouts	❑ Volcanology Rover ❑ Mars Smart Lander ❑ Magnetometer orbiter ❑ Synthetic Aperture Radar orbiter ❑ Imaging/Atmospheric Sounding orbiter ❑ Surface Science orbiter ❑ Polar Layer Deposit Lander/Rover ❑ Mars Sample Return ❑ Wildcat Lander ❑ Sabertooth Lander ❑ Scout mission

Notwithstanding these benefits, the approach did have a number of limitations.

Limitations and Improvements

The first issue surfaced by the Mars Systems Engineering Team involved questions about the uncertainties in technology definitions and data quality. While it was acknowledged that estimation of costs and technology development over a twelve-year horizon was difficult, it was argued that having the ability to examine the effects of data variability was at least a first step toward understanding how such estimates might be improved. A second round analysis was recommended by the Mars Systems Engineering team to refine and improve the definitions of missions, technology attributes, and data values. This task was initiated and is in progress.

A second issue was the effect of temporal dependencies between missions in a portfolio. The sequencing of missions is a process designed to provide "feed-forward" information from one mission to the next. For example, mapping by an orbiter could be used to improve knowledge about future landing sites for landed missions. The current methodology assumed independent missions.

However, if other missions depended on that failed mission for their technology development, they should also be removed from the feasible set. Such removals would also need to properly account for the portfolio science value since the maximum criterion as used in the present study could overstate the portfolio science value. A related capability to gracefully degrade technologies in the event failures occur was also seen as important by the Mars Systems Engineering Team for identifying task development shortfalls that provide acceptable technology deliveries. Both of these capabilities have been added to address such concerns.

A third limitation was the focus on technology investment costs and budgets when such values were between $1/5^{th}$ and $1/16^{th}$ of the total mission costs. Current efforts include the ability to compute total mission costs for each portfolio and compare to a mission budget constraint. This will eliminate technology portfolios that might have fit within the technology investment budget but whose missions taken together exceed the mission budget.

During the course of developing and applying the R&D portfolio model, a number of conclusions were drawn.

- ❑ At the lowest technology funding levels, the in-situ science strategy was not feasible. Low levels of technology funding implied an orbiter-based program.

- ❑ The highest level of technology funding proved to enable all missions and technologies in the portfolio under the current assumptions. As science goals evolve and mission concepts are added, modified, and deleted, different technology portfolios would be derived.
- ❑ The inclusion of technology cost profiles and budget constraints immediately focused attention on feasible options by eliminating the portfolios. This was not a complex model, but simple addition and subtraction. At the $50M/yr level, 89% of the portfolios were eliminated; at the $25M/yr level, 94% of the portfolios were eliminated.
- ❑ The methodology provided a systematic rationale that linked enabling technologies to missions and identified high-science value technology portfolios that minimized technology costs.
- ❑ The R&D portfolio approach helped clarify understanding between mission planners and technology developers

The application of the systematic tools and techniques described in this paper to Mars technology and mission planning provided a quantifiable and traceable approach to Mars Program personnel about science, technology, and mission interdependencies. The identification of high-value portfolios was seen as a first step toward making appropriate technology investments for defining the pathway to Mars.

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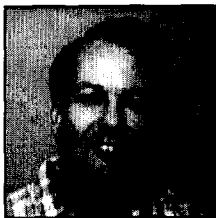
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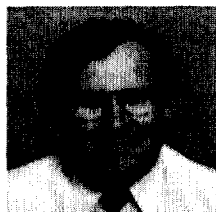
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